Soil & Tillage Research 105 (2009) 1–11

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Macronutrient concentration in plant parts of cotton fertilized with broiler litter in a marginal upland soil

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ARTICLE INFO

Article history:
Received 15 September 2008
Received in revised form 22 April 2009
Accepted 27 April 2009

Keywords:
Poultry litter
Manure
Incorporation
Tillage
Tissue nutrients

ABSTRACT

Effectiveness of surface-applied unincorporated broiler litter as a fertilizer relative to conventional inorganic fertilizers under no-till or conventional-till cotton (*Gossypium hirsutum* L.) production systems in the upland soils of the southern and southeastern USA is not well documented. The objectives of this research were to (1) test if broiler litter improves plant macronutrient (N, P, K, and Mg) nutrition of cotton above that of cotton fertilized with conventional inorganic fertilizers and (2) determine if lack of incorporating litter into the soil reduces macronutrient concentration in cotton plant parts in an upland soil considered marginal for cotton. Six treatments consisting of an unfertilized control, a fertilized standard (STD), two litter-only, and two litter plus inorganic N as urea–ammonium nitrate solution (UAN) were tested in two adjacent fields, one under no-till (NT) and the other under conventional-till (CT) systems. Litter alone, UAN, or a combination of litter plus UAN were applied to supply 101 kg ha^{-1} plant available N assuming nearly all of the UAN-N and 50% of the total litter N becomes plant available during the cotton growing season. Concentration of N, P, K, and Mg were measured in leaves, stems, and reproductive parts on three or four dates between early flowering and maturity. Cotton fertilized with the litter-only treatments always had less N concentration but greater P and K concentration in leaves, stems, and reproductive parts than cotton that received the STD treatment. Leaf and stem Mg concentration seems to depend on the N concentration in these plant parts. Lack of incorporating litter into the soil reduced N concentration in nearly all plant parts at all growth stages, suggesting some amount of the litter-derived N is lost due to lack of incorporation. Lack of incorporation also reduced leaf and stem Mg concentration, which seemed to be due to its reducing effect on N concentration. Unlike N and Mg, lack of incorporation did not consistently affect concentrations of P and K in all plant parts. Regardless of the incorporation treatment, fertilization with the litter-only treatments increased tissue P and K concentration and supported lint yield exceeding that of the STD without increasing tissue N concentration.

1. Introduction

Broiler litter is increasingly being used as a row crop fertilizer in the southern and southeastern United States, because it has been shown to be an effective fertilizer and is generated in abundance in the region (Tewolde et al., 2007a; Mitchell and Tu, 2005). Additionally, litter is much less expensive than synthetic fertilizers particularly in the last few years when fertilizer prices have nearly doubled. Litter may also be a more effective fertilizer than conventional inorganic fertilizers in marginal upland soils which tend to be low in organic matter, pH, and productivity.

Broiler litter as a fertilizer may be surface applied to row crops by broadcasting and left on the soil surface with no incorporation if no-till or reduced-till has been adopted as a management practice. In some situations, regardless of the tillage, it may not be possible to incorporate if the litter is applied after planting or after plant emergence. In other instances, the soil may be too wet to till and incorporate the litter. No incorporation may also be chosen to reduce cost regardless of the tillage practice.

Lack of incorporating the litter into the soil exposes litter and its nutrients to increased risks of loss due to volatilization or movement in runoff water. Litter contains all essential plant nutrients (Jackson et al., 2003) but is applied to crops primarily as a

Abbreviations: BL_i, incorporated litter; BL_{ni}, unincorporated litter; BL_i + UAN, incorporated litter plus UAN; BL_{ni} + UAN, unincorporated litter plus UAN; CT, conventional-till; DAP, days after planting; NT, no-till; STD, standard fertilization; UAN, urea–ammonium nitrate solution; UTC, unfertilized control.

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0167-1987/$ – see front matter © 2009 Published by Elsevier B.V.
doi:10.1016/j.still.2009.04.007

source of N which is the nutrient most vulnerable to volatilization loss. When left on the soil surface in the summer, as much as 24% volatilization loss of litter-derived NH_3-N has been reported, with the greatest loss occurring in the first week of application (Sharpe et al., 2004).

Nitrogen in forms other than NH_3 and the other nutrients including P and K can also be lost to runoff water by mass transport. Usually, such losses occur because of greater litter exposure, which leads to greater mass transport of the litter. Incorporation has been shown to reduce concentration of nutrients derived from litter or other manures in runoff water (Tarkalson and Mikkelsen, 2004; Daverede et al., 2004; Volf et al., 2007). Regardless of the incorporation, certain nutrients derived from litter may be more susceptible to runoff loss than nutrients derived from inorganic fertilizers (Tarkalson and Mikkelsen, 2004; Vories et al., 2001).

The magnitude of litter benefit reduction due to lack of incorporation and the extent of conservation of litter-derived nutrients in the soil by incorporation in cotton production systems is not well researched. Further, the effectiveness of surface-applied unincorporated litter as a fertilizer under no-till or reduced-till cotton production systems in the upland soils of the southern and southeastern USA relative to conventional inorganic fertilizers is not well documented. The objectives of this research, therefore, were to (1) test if broiler litter improves the macronutrient (N, P, K, and Mg) nutrition of cotton above that of cotton fertilized with conventional inorganic fertilizers and (2) determine if lack of incorporating litter into the soil reduces the macronutrient concentration in cotton plant parts under no-till and conventional-till systems in a sloping marginal upland soil. Lint yield (Tewolde et al., 2008) and soil nutrient concentration (Adeli et al., 2008) from the same study have been reported separately.

2. Materials and methods

The research was conducted from 2003 to 2005 at the Mississippi Agricultural and Forest Experiment Station near Pontotoc, MS (34°8′30″N, 88°59′36″W, 165 m alt.) in an Atwood silt loam soil (fine-silty, mixed, semiactive, thermic Typic Paleudalfs) with ≈2% slope.

2.1. Treatments and design

Six treatments of an unfertilized control, a fertilized standard, an incorporated and a non-incorporated litter-only, and an incorporated and a non-incorporated litter plus inorganic N as urea–ammonium nitrate solution (UAN) were tested in two unreplicated adjacent fields, one under no-till (NT) and the other under conventional-till (CT) systems. The six treatments were tested in a randomized complete block design replicated four times within each tillage field. Each plot consisted of six 13.7 m-long rows spaced 1.01 m apart.

The soil pH about a month before planting in 2003 was 6.30 ± 0.13 in the NT field and 6.58 ± 0.13 in the CT field. The entire NT field received about 560 kg ha^{-1} lime ($CaCO_3$) ≈ 2 weeks before planting in 2003 to increase the soil pH to approximate that of the CT field. The treatments under each field included an unfertilized control (UTC), a standard fertilization (STD) that received UAN-N plus inorganic P and K if recommended based on soil test, incorporated fresh broiler litter to supply 67% of the N requirement plus UAN to supply 33% of the N requirement, unincorporated fresh broiler litter to supply 67% of the N need plus UAN to supply 33% of the N requirement, incorporated fresh broiler litter to supply 100% of the N need, and unincorporated fresh broiler litter to supply 100% of the N requirement (Table 1). The incorporated treatment in the NT field was included to measure reductions in tissue nutrient concentration due to the inherent lack of incorporation. This treatment will be referred to as the incorporated treatment in the NT field for purposes of comparison in discussing the results although, under typical production practices, it may also be referred to as minimum till depending on the magnitude of incorporation and residue turnover.

Litter rate to deliver target N amount was determined assuming 50% of the total litter N becomes plant available for plant uptake within the cotton growing season. Litter alone, UAN, or a combination of litter and UAN were applied to supply 101 kg ha^{-1} plant available N (Table 1) based on general N recommendations for Mississippi (McCarty, 2006) for a target yield of ≈1000–1100 kg ha^{-1} lint, which is a reasonable expectation for this upland soil. A plot received the same treatment each of the 3 years under each tillage with the exception of inadvertently applying 101 kg ha^{-1} UAN-N instead of the planned 34 kg ha^{-1} UAN-N to the litter plus UAN treatments in 2004.

2.2. Treatment application

The litter in 2003 and 2004 was surface-applied in both the NT and CT fields on 29 April 2003 and on 19 May 2004 with a small-plot spreader with ≈150 kg litter-holding capacity. The spreader was equipped with a system that controlled application rate and dispensed the litter evenly across a 1.8-m swath. Immediately

Table 1
Amount of broiler chicken litter (BL) and total macronutrients (N, P, K, and Mg) applied to no-till and conventional-till cotton fertilized with litter and urea–ammonium nitrate (UAN) solution near Pontotoc, MS.

Treatment	Season	Applied litter (Mg ha^{-1})	Total N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Mg (kg ha^{-1})
UTC[a]	All	0	0	0	0	0
STD	2003	0	101	20[b]	37	0
	2004	0	101	20	0	0
	2005	0	101	20	0	0
BL_i + UAN, BL_{ni} + UAN	2003	5.5	142 + 34[c]	71	125	27
	2004	5.1	140 + 101	58	97	19
	2005	5.1	123 + 34	57	96	20
BL_i, BL_{ni}	2003	8.2	212	107	187	41
	2004	7.6	211	88	146	28
	2005	7.6	185	86	145	30

Litter-derived nutrient amounts were calculated by multiplying applied litter weight by concentration of the respective nutrient. The standard treatment (STD) received N as urea–ammonium nitrate solution (UAN), P as triple super phosphate, and K as potassium chloride.

[a] UTC = unfertilized control; STD = standard fertilization; BL_i + UAN = incorporated litter plus UAN; BL_{ni} + UAN = unincorporated litter plus UAN; BL_i = incorporated litter-only; BL_{ni} = unincorporated litter-only.

[b] Shown P amount applied to the STD treatment under no-till each of the 3 years. The STD under conventional-till received no P in any year.

[c] First N value derived from litter and second N value derived from urea–ammonium nitrate solution.

Table 2
Moisture and nutrient content of broiler litter applied to cotton in northern Mississippi near Pontotoc in 2003–2005.

Year	Moisture (g kg^{-1})	C (g kg^{-1})	N (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})	Na (g kg^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Zn (mg kg^{-1})
2003	263	280	24.5	11.4	22.4	19.6	4.7	–	377	1149	385	342
2004	164	341	26.3	13.0	21.3	21.7	4.3	5.8	366	915	211	214
2005	228	271	24.3	11.3	19.0	21.4	3.9	4.6	292	1356	183	171
Average	218	297	25.0	11.9	20.9	20.9	4.3	5.2	345	1140	260	242

before application, the litter was passed through a device that broke large litter pieces to pass a 12-mm screen to facilitate uniform flow. Because of mechanical failure with the spreader, litter in 2005 was spread by hand on 5 May 2005. Once applied by either method, the litter for the NT incorporated treatment was lightly incorporated into the top ≈0.05 m soil using a tractor-powered rotary tiller within 4 h after application. This procedure mixed the litter with a thin upper soil layer with little residue turnover. The soil below the 5 cm profile was not disturbed. The effect of the incorporation procedure was so small that the incorporated and non-incorporated treatments were indistinguishable from each other after ≈1 week following rainfall. Litter for the CT incorporated treatments was applied after disking followed by bedding, which served as the method of incorporation. A local broiler chicken producer supplied the litter, which was not composted. Moisture and selected element concentrations of the litter are shown in Table 2.

The inorganic N was applied as UAN solution (32% N) to the STD and the litter plus UAN treatments at the first square stage on 8 July 2003, 6 July 2004, and 23 June 2005 by soil injection about 0.15–0.20 m from the row center to a depth of ≈0.1 m using a commercial liquid fertilizer applicator equipped with knives and coulters. The STD treatment received other inorganic fertilizers based on local recommendations following soil analysis by the Soil Testing Laboratory of Mississippi State University. Background soil core samples were taken from the 0–0.15 m profile about a month before planting in 2003 and sent to the Soil Testing Laboratory of Mississippi State University for analysis and recommendation. Based on this analysis, the CT field had organic matter of 1.5% and extractable nutrients of 83 kg P ha^{-1}, 328 kg K ha^{-1}, and 160 kg Mg ha^{-1} about a month before planting in 2003. The NT field had 1.36% organic matter and extractable nutrients of 45 kg P ha^{-1}, 358 kg K ha^{-1}, and 207 kg Mg ha^{-1}. According to the recommendation, only the NT field needed to be fertilized with P each of the 3 years and both the NT and CT fields needed to be fertilized with K in the first year only. Inorganic P (0-46-0) and K (0-0-60) were applied to the STD as a broadcast by hand 15 d before planting in 2003, 12 d after planting (DAP) in 2004, and 7 DAP in 2005 as shown in Table 1. The soil had high (CT field) or very high (NT field) extractable Mg and, therefore, required no Mg fertilization.

2.3. Planting

Both the NT and CT fields were under no-till for at least 5 years prior to initiating this research. Beginning 2003, the CT field was prepared each year by disking once prior to planting, running a do-all (an implement consisting of a furrow opener, a rolling chopper, and a spiked-tooth harrow) to break clods and condition the beds, applying the litter to the incorporated treatments, and bedding up the entire field immediately. Both the NT and CT fields were planted with wheat (*Triticum aestivum* L.) cover crop each fall. Cotton cultivar 'DPL 451 BR' was planted in the Spring on 27 May 2003, 20 May 2004, and 6 May 2005 after killing the cover crop and any winter weeds with glyphosate [*N*-(phosphonomethyl) glycine] ≈15 d before planting. Weeds and insect pests were managed using conventional, recommended pesticides.

2.4. Measurements

Tissue nutrient concentration was measured on plant samples taken from the center four rows of each plot. Three or five plant samples selected to be typical to the plot were taken from each tillage field 73, 92, and 122 DAP in 2003; 56, 74, 88, and 126 DAP in 2004; and 76, 97, and 137 DAP in 2005. Plants sampled were cut at soil level, separated by hand into leaves (leaf blade + petioles),

Table 3
Monthly total rainfall and monthly average maximum and minimum air temperatures during the cotton growing season in northern Mississippi near Pontotoc, MS, 2003–2005.

Month	2003	2004	2005
Rainfall, mm			
May	246	248	46
June	151	229	91
July	80	117	127
August	225	88	212
September	246	248	46
Maximum temperature, °C			
May	25.5	26.6	25.3
June	27.6	28.3	28.6
July	30.1	30.1	31.7
August	31.0	28.8	32.5
September	27.2	27.7	29.9
Minimum temperature, °C			
May	16.1	17.0	13.2
June	17.6	19.6	19.0
July	20.8	20.0	21.8
August	21.1	18.0	21.6
September	15.9	16.6	18.4

stems (branches + main stem), and reproductive parts (squares + flowers + bolls). Plant parts were dried in a forced-air oven at 80 °C to constant weight, weighed, and ground to pass a 1-mm sieve. Reproductive parts were further separated into bur, seed, and lint after drying when bolls were mature enough to make the separation possible. Lint was separated from seed using a 10-saw gin. Seed samples were thoroughly delinted with concentrated H_2SO_4 (≈36 N) before grinding as linters on seed made homogenization difficult.

Total N concentration in the plant parts was determined by an automated dry combustion method using a ThermoQuest (CE Elantec Inc., Lakewood, NJ) C/N analyzer (Horneck and Miller, 1998). Concentration of P, K, and Mg in plant parts was determined by ashing 0.2 g of dry and ground sample in a muffle furnace at 500 °C for 4 h followed by digestion of the ash in 1.0 mL 6 M HCl for 1 h and 40 mL of a double-acid solution of 0.0125 M H_2SO4 and 0.05 M HCl for an additional 1 h. The digested solution was then filtered using a 2-V Whatman (Maidstone, UK) filter paper and analyzed for total P, K, and Mg concentrations using an inductively coupled dual axial Argon plasma spectrophotometer (ICP, Thermo Jarrell-Ash Model 1000, Franklin, MA) (Donohue and Aho, 1992). Reproductive N, P, K, and Mg concentrations were calculated as an average of seed, bur, and lint concentrations of these nutrients weighted by the respective dry weights of each sample. Lint nutrient concentrations were not analyzed as the nutrient content of lint is known to be low and varies little with fertilization (Fritschi et al., 2004). An average of 2.0 g N kg^{-1}, 0.6 g P kg^{-1}, 7 g K kg^{-1}, and 0.7 g Mg kg^{-1} lint was used for the calculation based on lint analysis from prior research (Tewolde et al., 2007b,c). Concentrations of these nutrients in litter were determined by the same method used for the plant parts (Table 2).

Daily weather data recorded at a National Weather Service's Cooperative Station Network located at the experiment station were downloaded from the National Climatic Data Center (NCDC, 2006). Maximum and minimum air temperatures were averaged and rainfall summed for each month during the cotton growing season (Table 3).

2.5. Statistical analysis

Effect of litter on concentration of the macronutrients was tested by subjecting the data to statistical analysis using mixed model analysis on SAS (Littell et al., 2002). Nutrient concentration data from the same growth stage were analyzed as a split plot with the fertilization treatments as the main plot in a randomized complete block design within each tillage field and the sub-plot was year as a repeated measure. This analysis was performed by pooling the data across the tillage fields which were treated as a fixed effect factor. Random effects for this analysis included replication within each tillage field and its interaction with year and fertilization treatments. Group comparisons were performed where well defined treatment structures existed. Some of these group comparisons included incorporated litter vs. non-incorporated litter regardless of rate, UTC vs. litter-only treatments regardless of incorporation, STD vs. litter-only treatments regardless of incorporation. All differences mentioned in the discussion are significant at $P \leq 0.10$ unless stated otherwise.

3. Results and discussion

Monthly total rainfall and monthly average maximum and minimum air temperatures in each of the three growing seasons were similar (Table 3). Total rainfall received during the critical part of the season in June, July, and August was 455, 434, and 430 mm in 2003, 2004, and 2005, respectively. The distribution of rainfall during these 3 months led to occasional but not to extended drought with rainfall totalling <100 mm in one of the 3 months each year. Maximum air temperature during June, July, and August were also similar each year. Only August was substantially cooler in 2004 than in 2003 or 2005.

Broiler litter, relative to the UTC and the STD treatments, distinctly affected concentrations of the macronutrients in the different cotton plant parts. Soil incorporating the litter, relative to no incorporation, also affected concentration of some of the macronutrients. These results will be discussed after pooling across years and tillage as interactions between treatments and tillage were non-significant. There was year by treatment interaction for tissue N concentration, but this was because of the two litter + UAN treatments which received 34 kg ha^{-1} UAN-N in 2003 and 2005 but, inadvertently, 101 kg ha^{-1} instead of 34 kg ha^{-1} UAN-N in 2004. As a result, tissue N concentration of these two treatments in 2004 was different from that of 2003 and 2005. This interaction will not be discussed further. Year by treatment interactions for tissue concentration of the other nutrients were non-significant or only marginally significant. The focus of the following presentation and discussion will be the effect of litter relative to the STD treatment and that of litter incorporation relative to no incorporation on tissue nutrient concentration pooled across tillage and years.

3.1. Effect of broiler litter application

3.1.1. Nitrogen

Application of broiler litter improved tissue N concentration relative to the UTC at all growth stages (Fig. 1 and Table 4). Relative to no fertilization (UTC), applying broiler litter with no incorporation and with no UAN-N supplementation increased leaf N by 16, 17, 25, and 9% at 56, 74, 92, and 128 DAP, respectively. Stem and reproductive N concentrations of the unincorporated litter-only treatment were also greater than that of the UTC on nearly all days.

However, cotton that received the litter-only treatments, despite receiving twice the amount of total litter N (Table 1), had consistently less N concentration in leaves, stems, and reproductive parts than cotton that received the STD treatment at almost all stages (Fig. 1 and Table 4). The STD treatment had leaf N concentration of 35, 40, 35, and 28 g N kg^{-1} which is 5, 19, 28, and 20% greater than that of the unincorporated litter-only treatment 56, 74, 92, and 128 DAP, respectively. Stem N concentration and reproductive N concentration of the litter-only

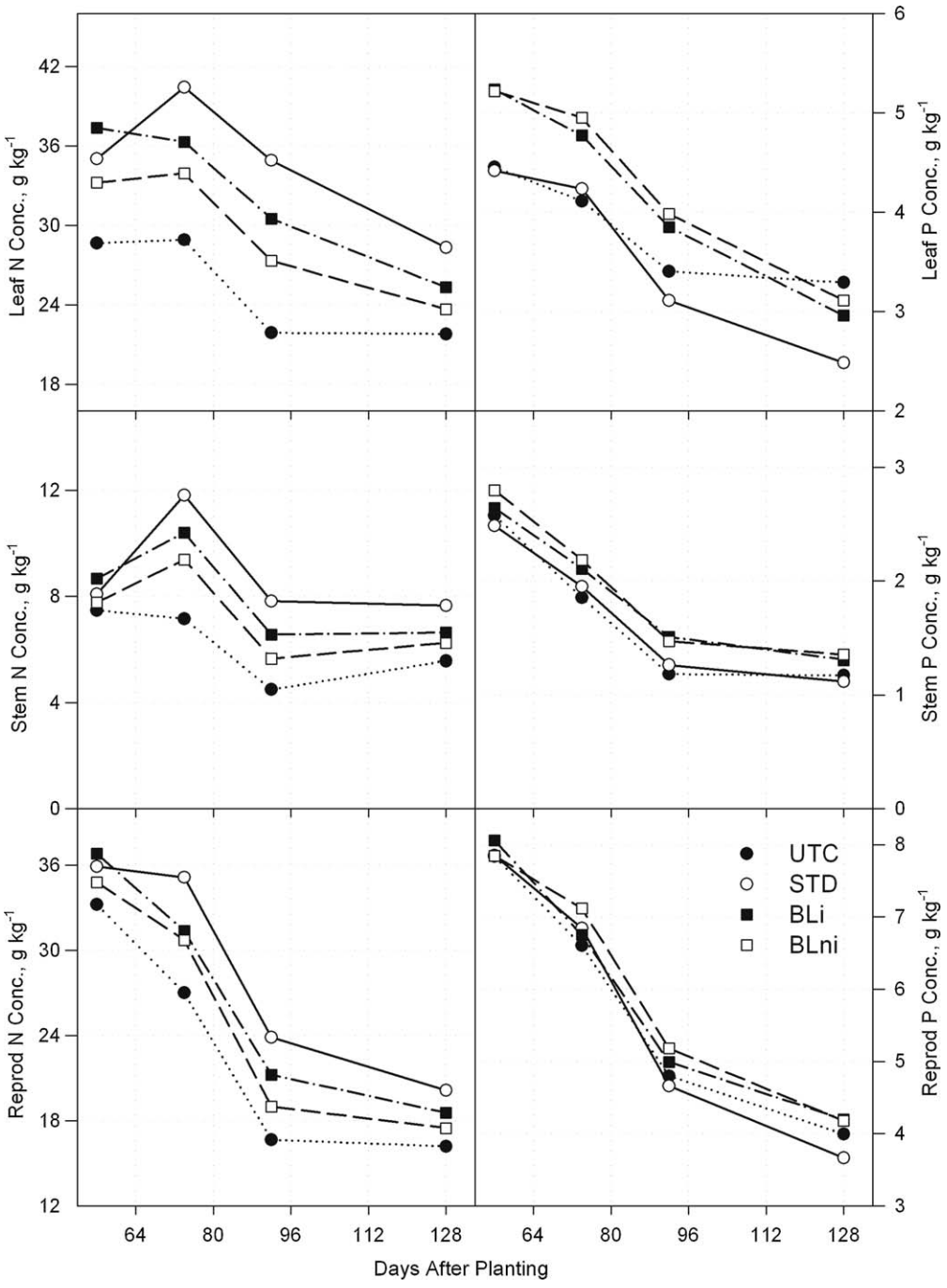

Fig. 1. N and P concentrations in plant parts of cotton fertilized with broiler litter and urea–ammonium nitrate solution. Each data point was pooled across two tillage fields (NT and CT) and 3 years (2003, 2004, and 2005). All data were balanced with the exception that the first day (56 DAP) represents data from 2004 only. Data of two treatments that received a combination of litter and UAN-N have been omitted to improve presentation.

treatments were also consistently less than that of the STD at nearly all stages. The effect of litter-only treatments on N concentration in all three plant parts, relative to the STD, usually was not dependent on tillage field or year. The lack of tillage field or year × (STD vs. litter-only) interaction at all growth stages except at 74 DAP (Table 4) suggests the greater tissue N concentration of the STD treatment than the litter-only treatments was consistent across years and the tillage fields. The significant year × (STD vs. litter-only) interaction 74 DAP is because, in 2005, the difference between the STD and the litter-only treatment was small (only ≈5%) compared with >10% in the other 2 years.

These results suggest cotton that received the litter-only treatments was seemingly under-fertilized. Chlorophyll index measurements and visual inspection of plant stand also seemed to suggest cotton that received the litter-only treatments was under-fertilized (Tewolde et al., 2008). The litter-only treatments in fact looked more similar to the UTC than to the STD treatment much of the mid-season. However, the early to late bloom bulk leaf N concentration of all treatments but the UTC fell within published sufficiency ranges of 30–45 g kg^{-1} (Mitchell and Baker, 2000). Lint yield and leaf area index results, which were published earlier, also showed cotton that received the litter-only treatments was as productive as or more productive than the STD treatment (Tewolde et al., 2008), suggesting that greater leaf N concentration or greener foliage may not necessary translate into greater growth and lint production. It may also be an indication that nutrients other than N

Table 4
Group comparisons of N, P, K, and Mg concentration in plant parts measured at selected growth stages of cotton fertilized with broiler litter and urea–ammonium nitrate solution in northern Mississippi near Pontotoc, MS.

Contrast	$P > F$											
	Nitrogen			Phosphorus			Potassium			Magnesium		
	Leaf	Stem	Reproductive part	Leaf	Stem	Reproductive part	Leaf	Stem	Reproductive part	Leaf	Stem	Reproductive part
Early flower (56 DAP)												
STD vs. BL-only	0.879	0.752	0.977	<0.001	0.027	0.669	0.011	<0.001	0.065	0.280	0.570	0.837
TF × (STD vs. BL-only)	0.721	0.414	0.888	0.234	0.077	0.082	0.933	0.419	0.645	0.156	0.450	0.770
Y × (STD vs. BL-only)	–	–	–	–	–	–	–	–	–	–	–	–
STD vs. BL + UAN	0.118	0.063	0.844	0.012	0.129	0.921	0.154	0.001	0.691	0.093	0.563	0.048
UTC vs. STD	0.006	0.189	0.512	0.877	0.439	0.962	0.502	0.872	0.216	0.524	0.987	0.549
UTC vs. BL-only	0.001	0.073	0.467	0.001	0.160	0.630	0.060	0.001	0.002	0.076	0.583	0.372
TF × UTC vs. BL-only	0.245	0.074	0.935	0.320	0.657	0.955	0.443	0.122	0.425	0.610	0.376	0.960
I vs. NI, BL-only	0.059	0.060	0.617	0.947	0.183	0.429	0.842	0.225	0.987	0.135	0.561	0.204
I vs. NI, all litter	0.057	0.007	0.145	0.661	0.684	0.239	0.283	0.077	0.847	0.248	0.458	0.499
TF × (I vs. NI, all litter)	0.238	0.091	0.236	0.069	0.184	0.227	0.609	0.136	0.170	0.706	0.987	0.744
Late flower to early boll formation (74 DAP)												
STD vs. BL-only	<0.001	<0.001	<0.001	<0.001	0.003	0.581	<0.001	0.133	0.173	0.574	<0.001	0.566
TF × (STD vs. BL-only)	0.554	0.565	0.595	0.014	0.004	0.189	0.058	0.798	0.050	0.019	0.142	0.394
Y × (STD vs. BL-only)	<0.001	0.010	0.001	<0.001	<0.001	0.089	0.776	0.080	0.080	0.319	0.735	0.062
STD vs. BL + UAN	0.518	0.603	0.330	0.007	0.038	0.477	0.007	0.002	0.360	0.368	0.498	0.191
UTC vs. STD	<0.001	<0.001	<0.001	0.331	0.170	0.220	0.296	<0.001	0.008	0.336	<0.001	0.007
UTC vs. BL-only	<0.001	<0.001	<0.001	<0.001	<0.001	0.051	<0.001	<0.001	<0.001	0.578	0.003	0.010
TF × UTC vs. BL-only	0.009	0.211	0.016	0.148	0.925	0.441	0.002	0.005	0.180	0.027	0.071	0.147
I vs. NI, BL-only	0.018	0.036	0.301	0.168	0.280	0.063	0.330	0.844	0.349	0.012	0.196	0.009
I vs. NI, all litter	0.001	0.020	0.089	0.176	0.291	0.176	0.868	0.323	0.903	0.034	0.210	0.027
TF × (I vs. NI, all litter)	0.064	0.048	0.098	0.217	0.731	0.519	0.264	0.845	0.533	0.547	0.459	0.131
Boll expansion and maturation (92 DAP)												
STD vs. BL-only	<0.001	<0.001	<0.001	0.001	<0.001	0.028	0.052	<0.001	0.700	0.017	0.596	0.370
TF × (STD vs. BL-only)	0.283	0.345	0.236	0.293	0.201	0.429	0.705	0.718	0.966	0.816	0.857	0.612
Y × (STD vs. BL-only)	0.395	0.270	0.863	0.106	0.511	0.447	0.212	0.283	0.805	0.459	0.238	0.892
STD vs. BL + UAN	0.014	0.004	0.005	0.002	<0.001	0.163	0.079	0.009	0.812	0.869	0.661	0.785
UTC vs. STD	<0.001	<0.001	<0.001	0.238	0.245	0.536	0.823	0.005	0.157	<0.001	<0.001	0.316
UTC vs. BL-only	<0.001	<0.001	<0.001	0.024	<0.001	0.134	0.030	<0.001	0.045	0.012	<0.001	0.792
TF × UTC vs. BL-only	0.858	0.345	0.248	0.599	0.915	0.781	0.219	0.421	0.913	0.668	0.654	0.664
I vs. NI, BL-only	0.003	0.018	<0.001	0.593	0.571	0.394	0.352	0.152	0.814	0.007	0.022	0.314
I vs. NI, all litter	0.001	0.006	0.005	0.699	0.229	0.098	0.856	0.065	0.292	0.076	0.058	0.045
TF × (I vs. NI, all litter)	0.554	0.887	0.723	0.973	0.398	0.077	0.343	0.982	0.243	0.587	0.649	0.086
Mature, ≈50% open bolls (128 DAP)												
STD vs. BL-only	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	0.010	<0.001	0.003	<0.001	0.530	<0.001
TF × (STD vs. BL-only)	0.650	0.341	0.531	0.848	0.542	0.471	0.480	0.238	0.704	0.961	0.247	0.688
Y × (STD vs. BL-only)	–	<0.001	0.895	–	0.063	0.149	–	0.043	0.276	–	0.916	0.360
STD vs. BL + UAN	<0.001	0.068	0.098	0.225	0.021	0.003	0.054	0.002	0.069	<0.001	0.598	0.150
UTC vs. STD	<0.001	<0.001	<0.001	<0.001	0.269	0.002	0.605	0.115	0.650	<0.001	0.091	<0.001
UTC vs. BL-only	0.001	0.014	<0.001	0.093	<0.001	0.030	0.035	0.004	0.011	0.786	0.175	0.666
TF × UTC vs. BL-only	0.208	0.177	0.062	0.010	0.021	0.896	0.599	0.358	0.707	0.019	0.385	0.806
I vs. NI, BL-only	0.048	0.268	0.045	0.376	0.359	0.824	0.096	0.786	0.630	0.019	0.395	0.831
I vs. NI, all litter	0.005	0.050	0.062	0.690	0.604	0.989	0.375	0.130	0.464	0.076	0.109	0.675
TF× (I vs. NI, all litter)	0.464	0.706	0.480	0.577	0.766	0.445	0.987	0.801	0.696	0.659	0.552	0.658

Data are shown in Figs. 1 and 3.
STD = standard fertilization with inorganic fertilizers; BL = broiler litter; TF = tillage field; Y = year; UTC untreated control; I = incorporated; NI = non-incorporated.

were limiting to yield of the STD treatment. Leaf area index results, which were reported earlier, suggested that applying the litter at planting may have been an advantage to early-season growth relative to the STD which received the UAN-N at the first square stage (Tewolde et al., 2008).

3.1.2. Relationship of N concentration with leaf chlorophyll index

Nitrogen concentration in leaves and stems usually correlated well with leaf chlorophyll index which was reported earlier (Tewolde et al., 2008). The correlation between bulk leaf or stem N concentration and chlorophyll index was strongest when measured in early to mid-August (2–16 August) of each season (Table 5 and Fig. 2). The relationships were weaker when leaf N and chlorophyll index were measured earlier or later than this period. This suggests use of the chlorophyll index for N management and diagnosis purposes may be more effective around the first or second week of August for cotton planted in May. This period corresponds with the late flowering and early boll formation stages. Whether any N management measures taken at this stage can be effective is not known.

3.1.3. Phosphorus

Unlike N, P concentration in leaf, stem, and to some extent in reproductive parts of the litter-only treatments was greater than that of the STD or the UTC treatments (Fig. 1 and Table 4). The STD treatment had 4.4, 4.2, 3.1, and 2.5 g kg^{-1} leaf P concentration 56, 74, 92, and 128 DAP, respectively. Relative to the STD, the non-incorporated litter-only treatment increased leaf P by 18, 17, 28, and 25% to 5.2, 5.0, 4.0, and 3.0 g kg^{-1} 56, 74, 92, and 128 DAP, respectively. The litter-only treatments also had greater stem P concentration than the STD or the UTC at all stages. The litter-only treatments had greater reproductive P than the STD or the UTC only towards the end of the season.

The difference between the STD and the litter-only treatments in tissue P concentration was not dependent on tillage field or year at 92 or 128 DAP (Table 4) as the tillage or year × (STD vs. litter-only) interaction was not significant or only weakly significant. At 74 DAP, the STD vs. litter-only group comparison of leaf and stem P concentration significantly interacted with year or tillage suggesting that the differences between the STD and litter-only treatments were not the same each year or in each tillage field. The STD and the litter-only treatments did not differ in leaf and stem P concentration 74 DAP in 2003. In 2004, the litter-only treatments had an average of 35% more leaf P and 26% more stem P concentration than the STD. The litter-only treatments had greater leaf and stem P concentration than the STD in 2005 also but by a smaller magnitude (7% leaf and 6% stem P concentration).

Table 5
Pearson correlation coefficients (r) derived from regressing N concentration in plant parts on chlorophyll index measured with a chlorophyll meter on the youngest fully expanded leaf of cotton grown in northern Mississippi near Pontotoc, MS.

Date	Days after planting	Correlation coefficient		
		Leaf	Stem	Repro
8 August 2003	73	0.57	0.40	0.32
27 August 2003	92	0.43	0.56	0.45
26 September 2003	122	0.38	0.14	0.17
15 July 2004	56	0.26	0.39	0.17
2 August 2004	74	0.88	0.83	0.70
16 August 2004	88	0.78	0.81	0.61
11 August 2005	97	0.70	0.46	0.25
20 September 2005	137	0.45	0.48	0.59

Nitrogen concentration measured on plant parts collected from three or five plants per plot and three or four replications.

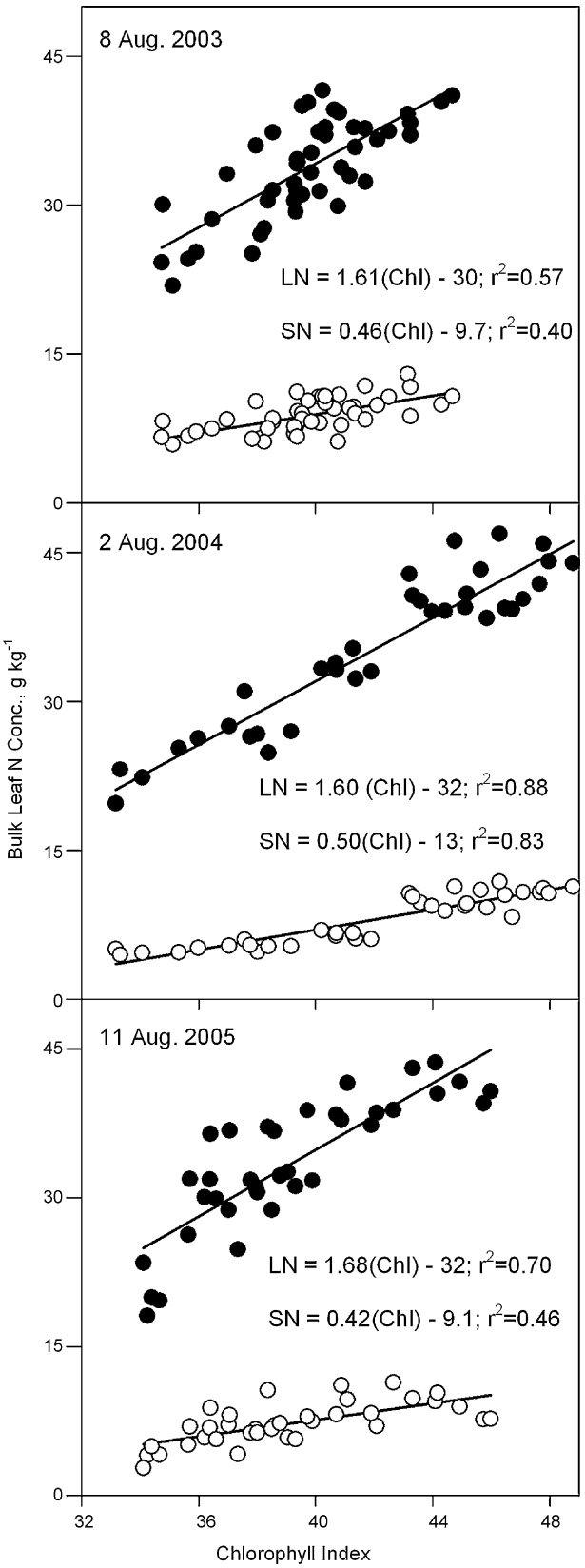

Fig. 2. Relationship of leaf (LN) and stem (SN) N concentrations with chlorophyll index (Chl) of cotton fertilized with broiler litter and urea–ammonium nitrate solution. Each data point is an average of three or four replications. All fitted lines are significant at $P < 0.0011$.

It is likely the greater leaf P concentration of the litter-only treatments than the STD treatment is related to the leaf N concentration level and to the level of applied P. The litter-only treatments received an average of 93 kg ha^{-1} year^{-1} litter-derived P (Table 1) compared with 20 kg P ha^{-1} year^{-1}as triple superphosphate in the NT field and no P fertilization in the CT field based on soil test recommendations. We believe the greater litter-supplied P contributed to the greater tissue P concentration in the litter-only treatments than the STD treatment. However, we also believe the greater tissue P concentration in the litter-only treatments than in the STD treatment is also related to the N nutrition of these treatments, because tissue P concentration appears to be inversely related to applied N (Evers, 2002; Tewolde et al., 2007b). Tewolde et al. (2007b) showed cotton that did not receive N or P fertilization had greater leaf P concentration than cotton that received adequate P and N fertilization. Although the litter-only treatments in this research received twice as much total N as the STD, leaf N concentration of the litter-only treatments was mostly less than that of the STD treatment. Therefore, the greater P concentration in leaves and other plant parts in the litter-only than in the STD treatment may be related to the less tissue N concentration of the litter-only than the STD treatment. The UTC, which had the least leaf N concentration, had leaf P concentration about the same as the STD 56 and 74 DAP but greater than the STD 92 and 128 DAP (Fig. 1). The UTC had nearly the same level of soil P concentration as the STD but had

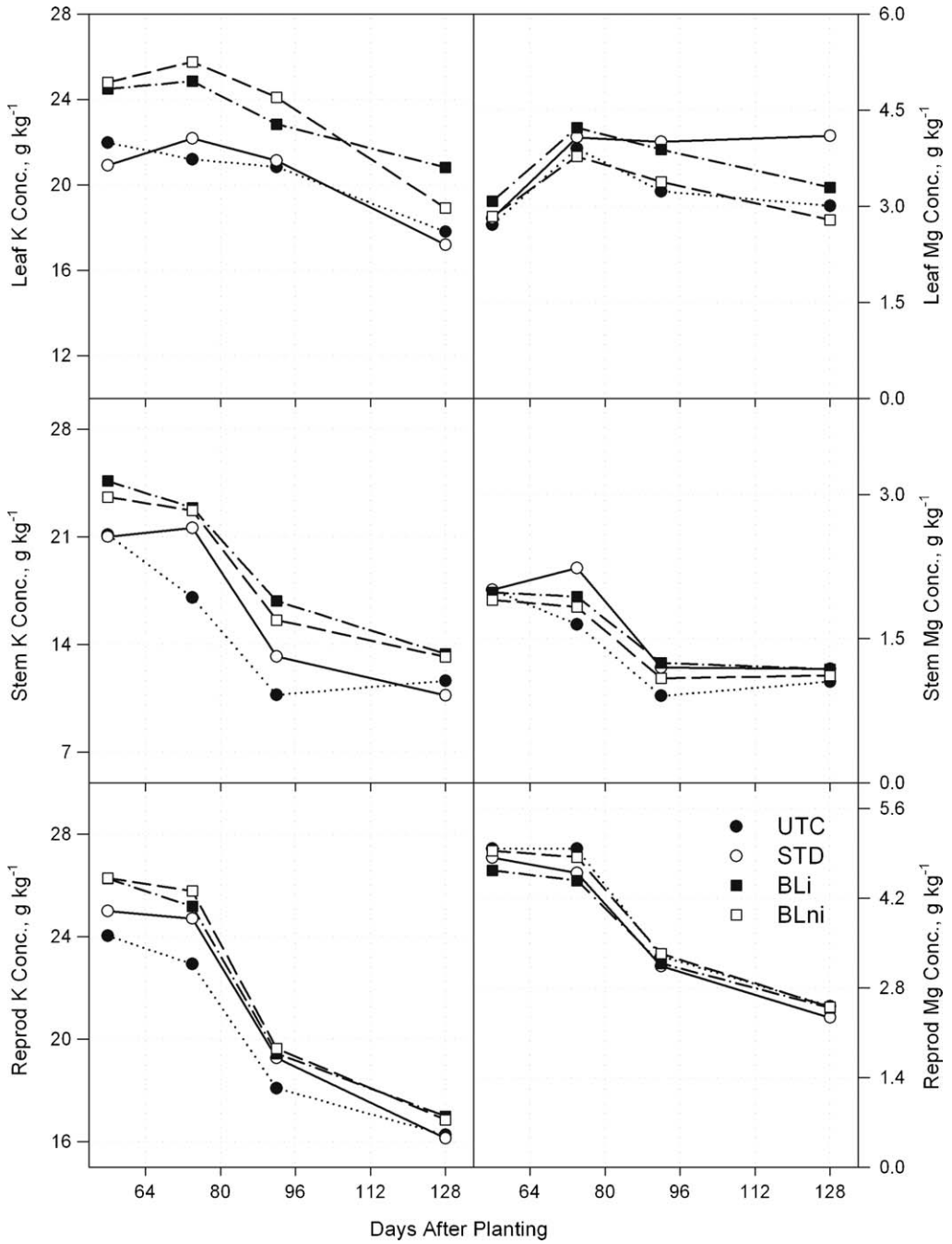

Fig. 3. K and Mg concentrations in plant parts of cotton fertilized with broiler litter and urea–ammonium nitrate solution. Each data point was pooled across two tillage fields (NT and CT) and 3 years (2003, 2004, and 2005). Data were balanced with the exception that the first day (56 DAP) represents data from 2004 only. Data of two treatments that received a combination of litter and UAN-N have been omitted to improve presentation.

significantly less soil P than the other treatments that received litter (Adeli et al., 2008).

Leaf P concentration at any of the four growth stages measured on all whole leaves of all treatments including that of the UTC ranged between 2.5 and 5.2 g kg^{-1}. The published P sufficiency level, based on the youngest fully expanded leaf blades measured during the late bloom and maturity stages, is 1.5–6 g kg^{-1} (Mitchell and Baker, 2000). This suggests P was not limiting to lint yield and growth in any of the treatments including the STD assuming guidelines established based on young single leaf blades applies to P concentration based on all whole leaves.

3.1.4. Potassium

Relative to the UTC, the litter-only treatments increased K concentration in leaf, stem, and reproductive parts at all stages (Fig. 3 and Table 4). These litter-only treatments also increased K concentration in leaf and stem over the STD. The litter-only treatments had only slight K concentration increases in reproductive parts. The STD and UTC had similar leaf K concentration, but the STD treatment usually had greater stem and reproductive K concentration than the UTC.

The greater tissue K concentration with the litter-only treatments than the STD treatment is likely due to the amount of applied litter-supplied K although the STD also received recommended rates of K. The litter-only treatments received an average across years of 159 kg ha^{-1} year^{-1} litter-derived K (Table 1). The STD received 37 kg K ha^{-1} as KCl in 2003 only, which was based on soil analysis and local fertilizer recommendations.

Results of the tissue K concentration, like the results of the tissue P concentration, suggest that the better yield performance of the litter-only treatments than the STD treatment (Tewolde et al., 2008) may be associated with the increased leaf and stem K concentration by the litter-only treatments. Leaf K concentration of all treatments including that of the UTC at any stage were within published sufficiency ranges of 7.5–25 g kg^{-1} when measured on the youngest fully expanded leaf during the late bloom and maturity stages (Mitchell and Baker, 2000). However, our leaf K concentration data may not be helpful for determining if K was limiting to yield because it was measured on all leaves and no sufficiency ranges based on bulk leaf K concentration have been developed. Older leaves are known to have greater K concentration than younger leaves (Tewolde et al., 2005).

3.1.5. Magnesium

The difference in tissue Mg concentration among the treatments was not as clear-cut as in the tissue concentration of N, P, or K (Figs. 1 and 3 and Table 4). Usually, the UTC had less leaf and stem Mg concentration than the STD and sometimes than the incorporated litter-only treatments. But, the UTC seemed to have greater or the same reproductive Mg concentration as the STD and the incorporated litter-only treatments 56 and 74 DAP.

Concentration of Mg in plant parts, unlike N and K, may be dependent on factors other than the nutrient supply. Magnesium was not applied as a separate fertilizer as the soil initially had high or very high extractable Mg levels (an average of 184 kg ha^{-1}) as determined by the Soil Testing Laboratory of Mississippi State University. But the litter used in this research contained an average across years of 4.3 g Mg kg^{-1}. Applying this litter to supply the full N need, delivering an average of 33 kg ha^{-1} year^{-1} litter-derived Mg (Table 1), did not increase Mg concentration in plant parts above the STD treatment which received no Mg fertilization (Fig. 3 and Table 4). In fact, at the end of the season, the STD had much greater leaf Mg concentration than either of the two litter-only treatments, which suggests leaf Mg concentration was not dependent on soil Mg availability. The STD treatment, despite receiving no Mg fertilization, also had greater Mg concentration in leaf, stem, and reproductive parts over the UTC on some days (Fig. 3 and Table 4). This increase in tissue Mg of the STD treatment over the UTC should be due to factors other than soil-applied Mg, since both the UTC and the STD treatments received no Mg fertilization.

Interestingly, leaf Mg concentration of the incorporated litter-only treatment was similar to that of the STD during the first 3 d (56, 74, and 92 DAP), while leaf Mg concentration of the unincorporated litter-only treatment was about the same as that of the UTC at all stages. The two litter-only treatments received an average of 33 kg ha^{-1} year^{-1} litter-derived Mg while the UTC and the STD received no Mg fertilization. This further confirms that leaf Mg concentration may be more related to the N nutrition of the crop than to Mg fertilization if the soil already contains adequate Mg. It is likely that better N nutrition enhances Mg nutrition of leaves. Regressing concentrations of leaf Mg on leaf N revealed a

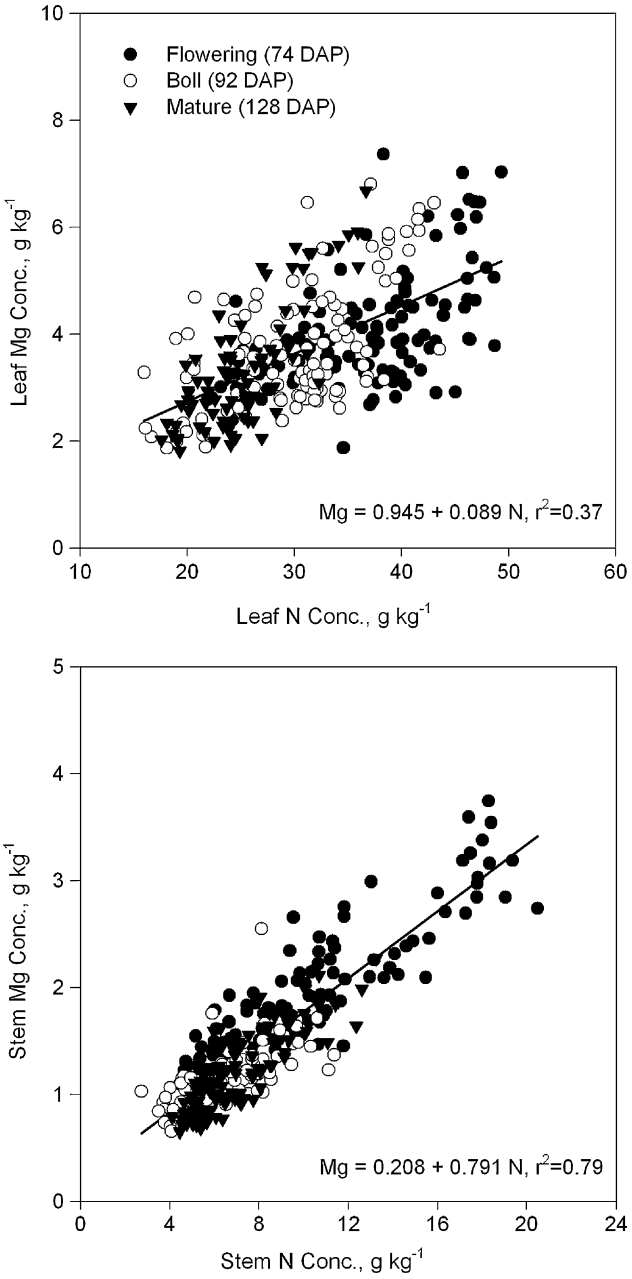

Fig. 4. Relationship between N and Mg concentrations in leaves and stems of cotton fertilized with broiler litter and urea–ammonium nitrate solution. Each data point is an average of three or four replications. The fitted lines are significant at $P < 0.0011$.

strong and highly significant ($P < 0.001$) positive relationship between the two measurements in the last 3 d with r^2 of 0.37 ($n = 311$) (Fig. 4). This relationship is consistent with the chemistry of the chlorophyll molecule, the center of which is occupied by both Mg and N (Epstein and Bloom, 2005). The relationship of N and Mg concentration was even stronger in stem than in leaves with r^2 of 0.79 ($n = 311$) (Fig. 4). This suggests soil Mg may have been adequate in all treatments, but the uptake and utilization of Mg may be dependent on the N nutrition status of the plants.

3.2. Effect of incorporation

Soil incorporated litter, relative to no incorporation, resulted in greater N concentration in nearly all plant parts (Fig. 1 and Table 4), suggesting incorporation conserved litter-derived N from loss to volatilization or runoff. Incorporation in the litter-only treatments, pooled across tillage fields and years, increased leaf N concentrations by 13, 7, 12, and 7%; stem N by 12, 11, 16, and 6%; and reproductive N by 6, 2, 12, and 6% over the no incorporation 56, 74, 92, and 128 DAP, respectively. Measurement of residual soil N at the end of the 3-year period in 2005 confirmed this N conservation (Adeli et al., 2008). The increased tissue N concentration due to incorporation was not dependent on tillage field (Table 4), suggesting incorporation was beneficial for litter N conservation in both the NT and CT fields. However, the increases due to incorporation did not bring N concentration in plant parts to equal to that of the STD treatment. Although better than the UTC and the unincorporated litter-only treatment, N concentration in plant parts of the incorporated litter-only treatment was still less than that of the STD treatment. Cotton that received the incorporated litter-only treatment had 3, 10, and 10% less leaf N concentration; 3, 11, and 19% less stem N concentration; and 7, 11, and 8% less reproductive N concentration than the STD treatment 74, 92, and 128 DAP, respectively. Although the percent increases appear to be small and did not bring tissue N to be as high as that of the STD treatment, the effect of incorporation on N nutrition is important considering it is due to reduced loss to volatilization or to runoff and considering it improved yield (Tewolde et al., 2008). Incorporation, relative to no incorporation, increased lint yield by ≈8%.

Litter incorporation affected leaf Mg concentration but, unlike the clear effect on N concentration in all plant parts, litter incorporation did not have any consistent effect on concentration of the other plant parts at any of the growth stages (Figs. 1 and 3 and Table 4). Incorporation increased leaf Mg concentrations by 8, 12, 15, and 18% over no incorporation 56, 74, 92, and 128 DAP, respectively. The effect of incorporation on leaf Mg concentration may be related to its effect on leaf N nutrition. It is likely that enhanced N nutrition may also enhance Mg nutrition of leaves. It is also possible litter incorporation could have protected litter Mg from loss to runoff and made more Mg available for plant uptake. But the fact that the STD treatment, which received no Mg, had as much as or more leaf Mg concentration than the incorporated litter-only treatment suggests that soil Mg availability is unrelated to the enhanced leaf Mg concentration in the incorporated treatment. As discussed earlier, uptake and utilization of Mg by cotton may be dependent on the N nutrition status of the plants rather than by the amount of Mg fertilization. Incorporation slightly increased Mg concentration in stems but decreased Mg concentration in reproductive parts occasionally. Incorporation did not consistently affect concentration of P and K in all plant parts at any of the growth stages. These results indicate that the increase in tissue N concentration due to incorporation probably is largely due to reduced volatilization loss instead of reduced runoff loss as the concentration of at least one of the nutrients P and K would have improved if runoff loss was reduced by incorporation.

4. Conclusion

Despite receiving twice as much litter-derived total N, cotton fertilized with broiler litter had consistently less N concentration in leaves, stems, and reproductive parts than cotton fertilized with the conventional fertilizer urea–ammonium nitrate solution. Interpreting this finding plus chlorophyll index measurements (Tewolde et al., 2008) and visual inspection of plant stand, without taking yield and growth performance into consideration, may seem to suggest fertilizing cotton with broiler litter leads to N under-fertilization. However, as reported earlier, lint yield and leaf area index results showed cotton fertilized with litter was as productive as or more productive than cotton fertilized with urea–ammonium nitrate (Tewolde et al., 2008). This shows cotton fertilized with broiler litter was not under-fertilized with N and that litter can be applied to cotton assuming 50% of the analytical N concentration becomes plant available during the growing season. Additionally, fertilizing cotton with broiler litter in this marginal soil may lead to greater P and K nutrition. Incorporation, relative to no incorporation, increased N concentration in all plant parts by 6–16% but did not consistently affect concentration of P and K in all plant parts at any of the growth stages. This suggests the increase in tissue N concentration of cotton when incorporating the broiler litter was due more to a reduction in volatile N losses than to loss of litter N in runoff.

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